Large Eddy Simulation of Sediment Transport in the Presence of Surface Gravity Waves, Currents and Complex Bedforms

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LONG-TERM GOALS

Our long-term goal is to develop numerical simulation techniques for generating accurate predictions of sediment transport and bed evolution in the coastal zone at horizontal scales of 10s of meters or less.

OBJECTIVES

Our earlier work has produced accurate hydrodynamics and sediment transport dynamics. Our first focus now is on nonhydrostatic motions and transport on scales of the order of meters and in the presence of waves and currents. Our second focus is to use a fully three-dimensional, nonhydrostatic, free-surface code to study both laboratory scale and field-scale motions and transport related to the burial and unburial of cobbles/mines. We seek to produce at the same time a sediment transport code without the typical parameterizations and approximations used in codes applied at the scales of kilometers.

APPROACH

Recently, we completed a simulation of channel flow with the Large Eddy Simulation [LES] code of Zedler and Street (2002). The approach for this simulation was the same as the approach for the simulations of T. Stanton's measurements of oscillatory flow over ripples at Duck, N.C. That code solves the three-dimensional, volume-filtered Navier Stokes equations for the momentum and an advection-diffusion equation with a settling term on a curvilinear grid. The Mixed Model [Bardina et al. 1983] has been used for representation of the sub-filter scale terms. We have implemented a log-law boundary condition and an extended boundary condition model for the treatment of rough boundaries in the context of filtering in LES. The code is second order accurate in time and space and non-hydrostatic.

In the current phase of our research, we will be using a considerably altered version of this code to study sediment transport around cobbles/mines. This requires both the implementation of a moving bed boundary and a set of lateral and top boundary conditions, which will allow the flow and sediment to pass through the region around a mine in an accurate way.

In order to address the moving bed issue, we are extending Tseng et al.'s (2003) fixed-bed implementation of the immersed boundary method [IBM] into the Zedler and Street (2002) code to

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allow for a moving bed in a large Reynolds number flow with a rough bottom. The IBM essentially inputs a forcing at the location of the bed to preserve the relevant boundary conditions. This technique is convenient numerically as it allows for the use of a fixed, Cartesian grid. We have already begun to implement this method for the scalar field.

High grid resolution will be necessary to fully capture the detailed bed motions. We plan to simulate some of J. Fernando's laboratory experiments on sediment transport around buried mines. The best grid resolution will be achieved in cases where the grid is focused around the buried mine, but this opens up the issue of specifying accurately the velocities at the inlet/outlet, top and lateral boundaries of the domain around the mine. The code of Grilli et al. (2001) will be used to specify these values; Prof. Grilli will be generating this data under a subcontract to this grant.

WORK COMPLETED

We have completed:
  (1) numerical simulation of large Reynolds number O(600,000) channel flow over a rough boundary, for the validation of the rough/log boundary module of the code for this simplest and well-known case, and
  (2) implementation of the IBM for the scalar field.

RESULTS

Results from the channel flow simulation illustrate two important concepts; they have been written into a paper being submitted to the Journal of Hydraulic Research. First, when the streamwise velocity and concentration profiles are averaged in time, one recovers the well-known Rouse concentration and log velocity profiles. Second, the three velocity components and sediment concentration computed by the LES code fluctuate over very fast time scales at a point in space and exhibit strong spatial variability at an instant in time. From these results we have been able to establish that the rough boundary implementation in the code is able to predict accurately the correct time-averaged behavior.

Figure 1 shows the time averaged velocity and Rouse concentration profiles. The streamwise velocity profile is logarithmic to a distance of $y+ \sim 1000$, as it should be according to Hinze (1959). Its shape is similar to the profiles obtained in other LES simulations [e.g., Gullbrand and Chow (2003)]. The Rouse curve [with an assumed parabolic eddy viscosity] is plotted together with the time- and horizontally- averaged concentration profile above two levels [one close to the bed and one at 0.05H, where H is the channel depth]. Here, the simulated concentration values have been normalized by their respective mean values at these levels, consistent with the definition of the Rouse curve. The Rouse curve has been generated with the shear velocity estimated from the driving pressure gradient used in the simulation, a turbulent Schmidt number of 1, and a von Karman constant of 0.41. Excellent agreement between the Rouse curve and simulation results has been achieved.
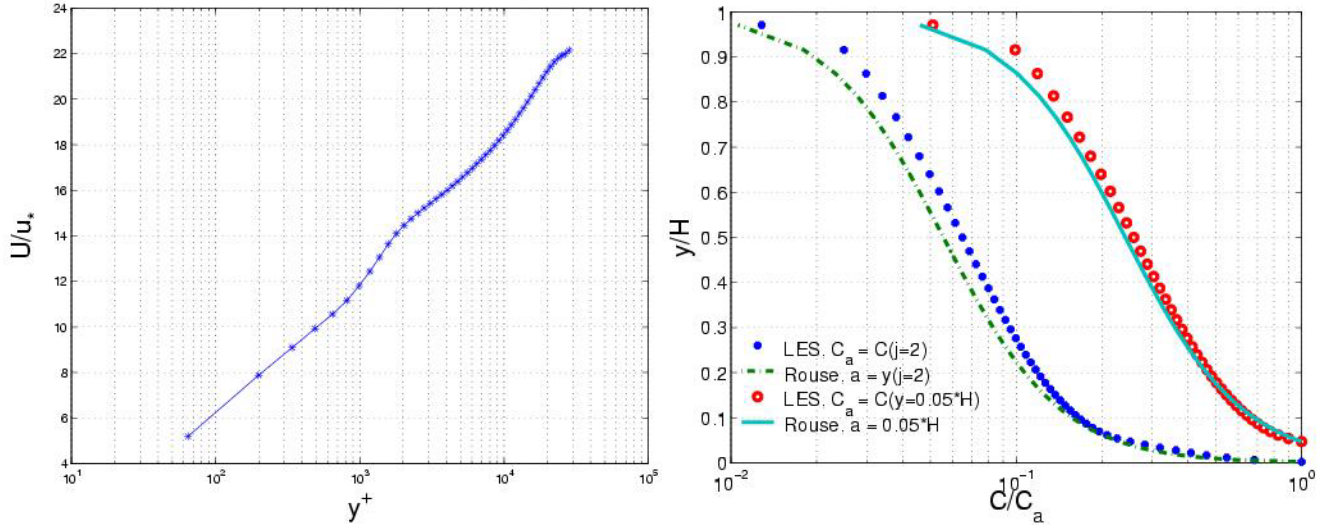
Figure 1. (a) Time-averaged streamwise velocity profile, normalized by the shear velocity and plotted against $y^+= (u*y)/v$. (b) The Rouse curves, plotted together with the time-averaged concentration profiles.

The "large" eddies, or organized motions, which contribute to this well-established time-averaged behavior are resolved and produce a robust description of instantaneous sediment transport. Figure 2a illustrates the time-fluctuating sediment concentration and streamwise velocity at various distances above the bed. Figure 2b summarizes the three-dimensional spatial variability of sediment concentration and velocity fields at an instant in time. The velocity vectors in Figure 2b are projected onto a streamwise vertical plane [left] to show the log velocity layer and a spanwise-vertical plane to show the circulation in the plane perpendicular to the main channel flow. The elongated structures represent regions of low pressure and are plotted as iso-contours of λ_2 [a surrogate for the pressure minimum in a plane of arbitrary orientation, Jeong and Hussain (1995)]. The colors represent the sediment concentration contours on each surface. The strong spatial variability in the sediment concentration field is due partially to that of the velocity field and partly to the preferential pickup of sediment in regions where the shear stress is highest. While the spanwise-vertical component of the velocity is primarily responsible for mixing sediment across the channel, the streamwise component advects these strong gradients in concentration through the channel and leads to the high frequency time fluctuations plotted in Figure 2a.
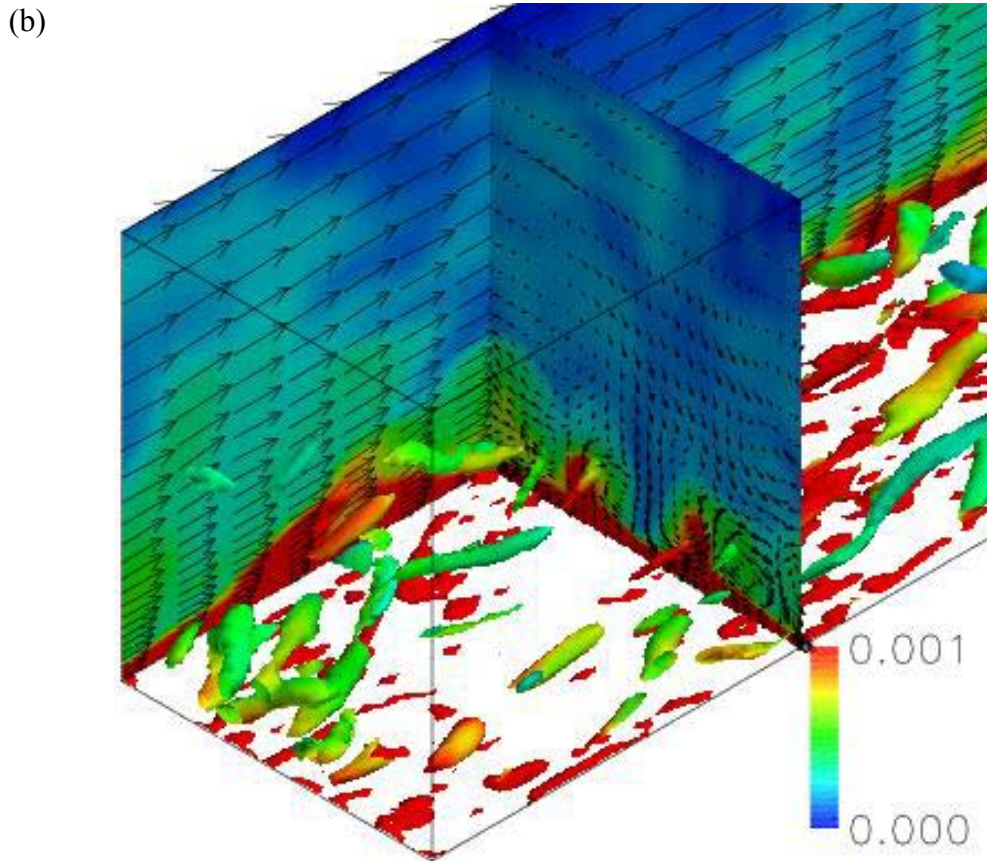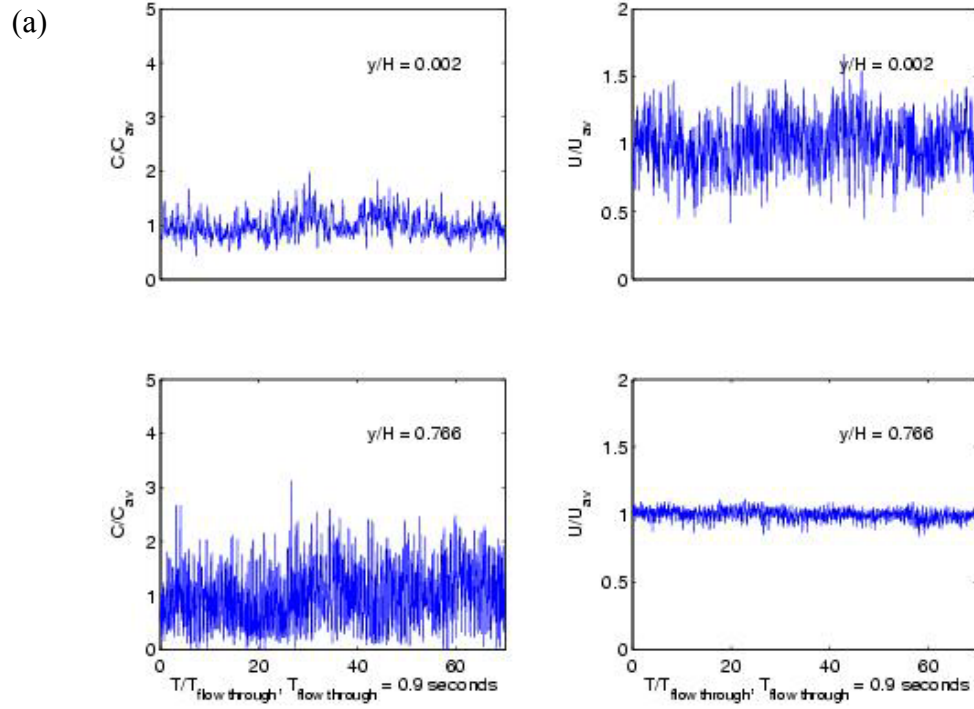
(a)

(b)

Figure 2. (a) Time series of concentration and the streamwise velocity at various heights above the bed. (b) An instantaneous picture of the sediment concentration contours [colors], velocity vectors, and elogated regions of low pressure [coherent eddy structures].

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IMPACT/APPLICATIONS

We are developing a simulation tool that includes large-scale forcing by the Grilli potential flow code, detailed representation of near-bed motions and transport by large-eddy simulation, and use of the immersed boundary method to trck bed evolution. This tool has great potential for understanding and predicting the burial and unburial of objects on the coastal ocean bed and for predicting ripple and dune formation and evolution.

RELATED PROJECTS

Professor Stephan T. Grilli, U. Rhode Island, is providing support for this work through a subcontract under this grant.

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PUBLICATIONS

Zedler, E.A. and Street, R.L. (2002) Nearshore sediment transport processes: unearthed by Large Eddy Simulation, *28th International Conference on Coastal Engineering*, ASCE, pp. 2504-2516.

HONORS/AWARDS/PRIZES

2002 Karl Emil Hilgard Hydraulic Prize awarded by the American Society of Civil Engineers to Dr. Zedler and Prof. Street for the paper: Zedler and Street (2001) cited above.